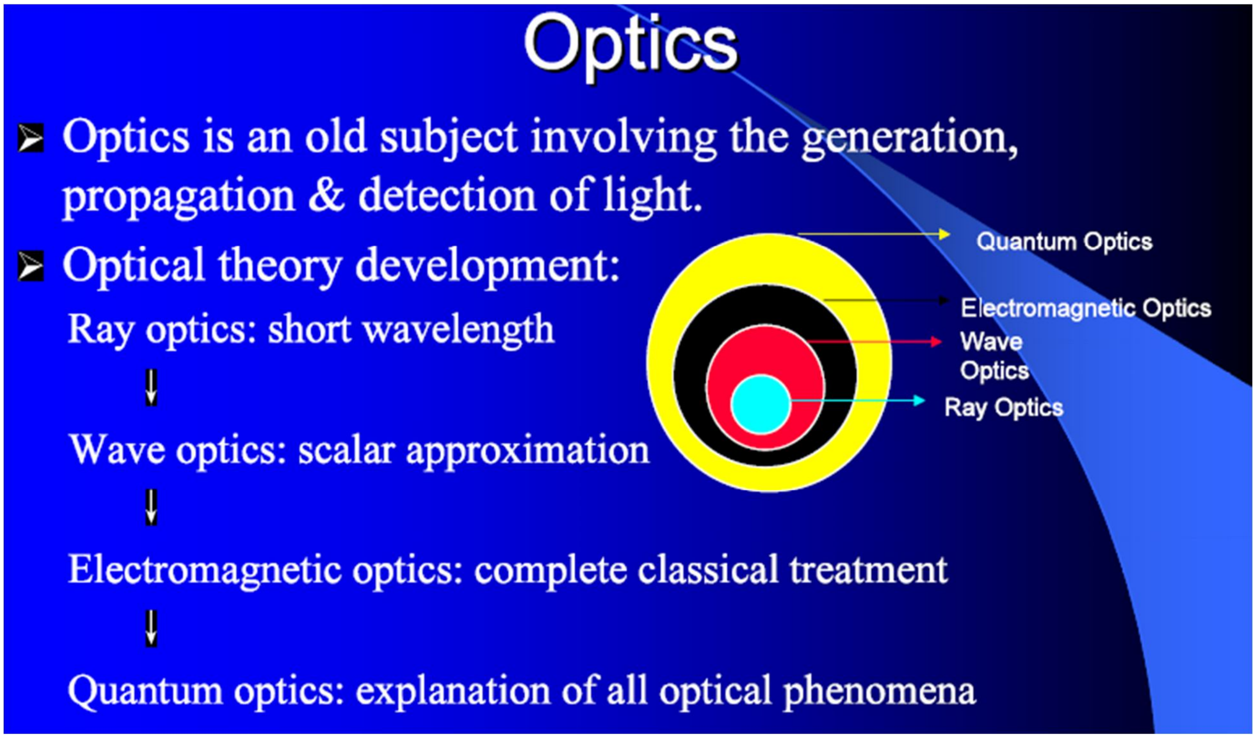
Optical Fiber Basics



The question of what light "really is" can be elusive. Light is usually described in one of three ways:

1- Rays:

In the classical physics that many of us learned at school, light consisted of "rays" that could be reflected and refracted through mirrors and prisms etc. This is a good description as far as it goes but it cannot explain many of the phenomena we make use of in optical communications. The problem is that when you try to study "rays" very closely they start behaving like waves. For example, if you pass a beam of light through a small hole or slit about the same diameter as the wavelength the "ray" spreads out at the edges (it diffracts). Neither of these phenomena (diffraction or interference) are consistent with a ray description.

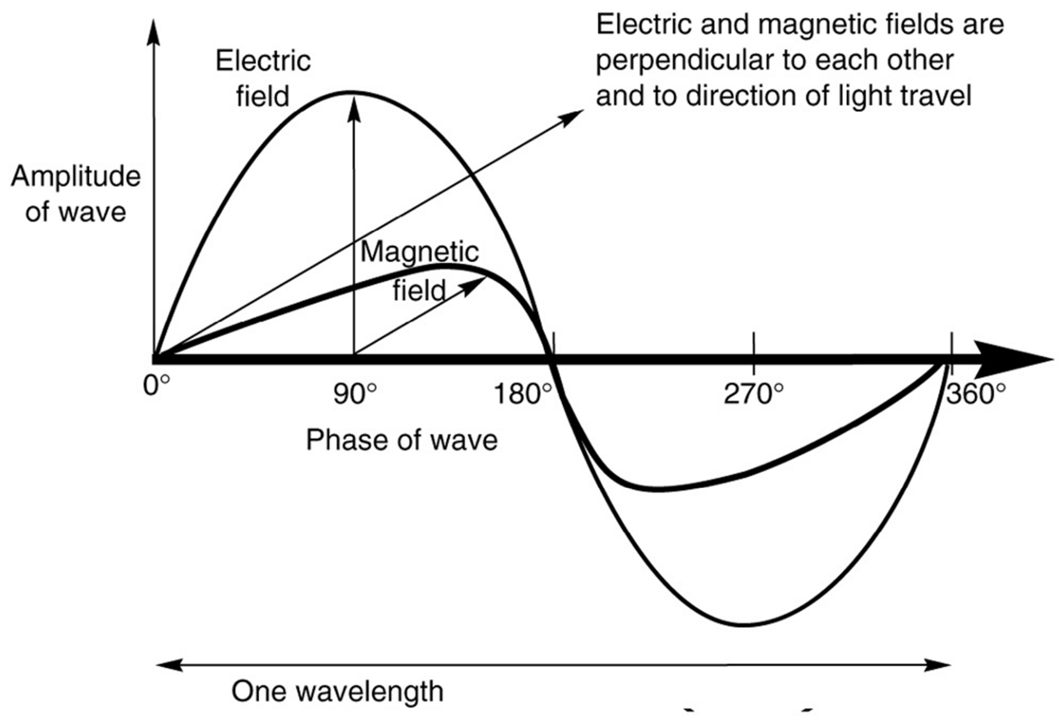
2- Electromagnetic Waves:

In the context of optical communications, most of the time it will be found that the best way of regarding light is to think of it as an electromagnetic wave. In this view it is no different from a radio wave except that the wavelength is much shorter! It is the only satisfactory way of conceiving of light propagation in a single-mode fiber, the operation of a Bragg grating or the operation of optical couplers and splitters.

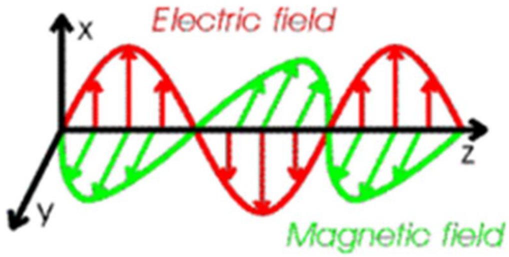
Wave Propagation

Electric and magnetic fields are at right angles to each other and to the direction of travel.

- This is called a transverse electromagnetic (TEM) wave
- Wavelength (λ) is the distance the wave travels in one period (T).



EM wave move through a vacuum at 3.0×10^8 m/s ("speed of light")



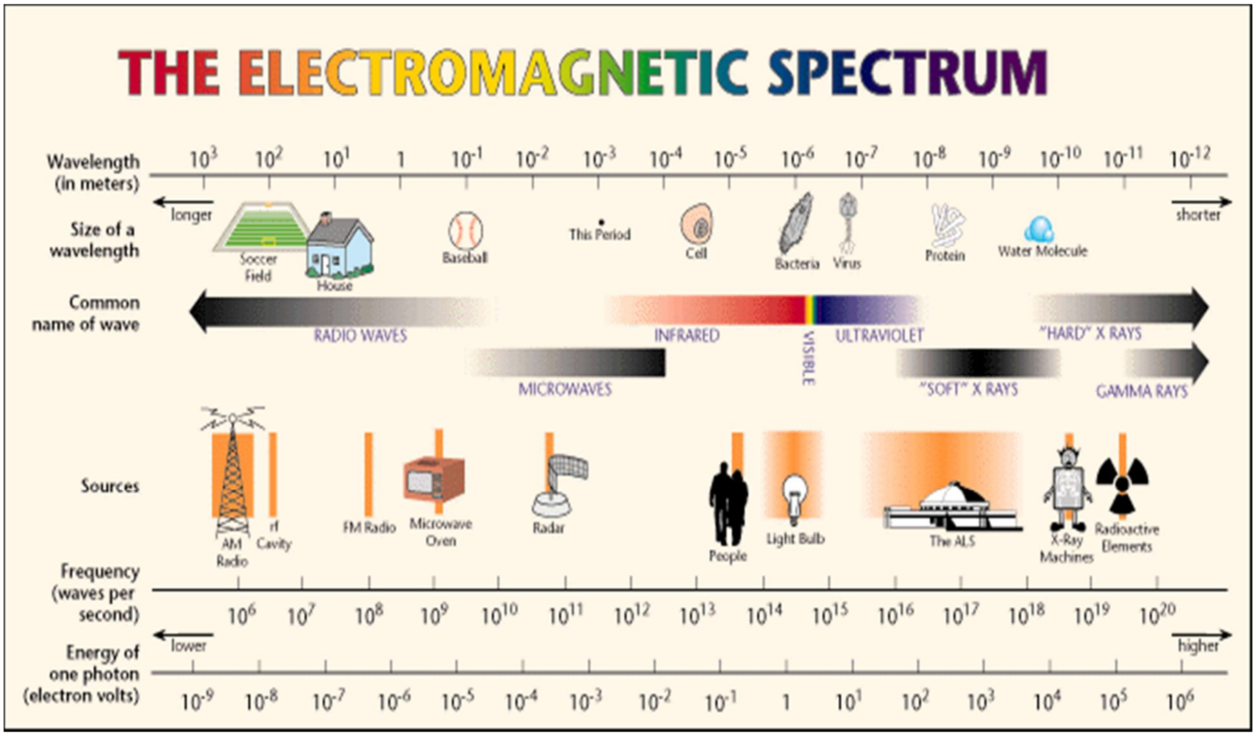
Speed of light in a vacuum $c = f \times \lambda$

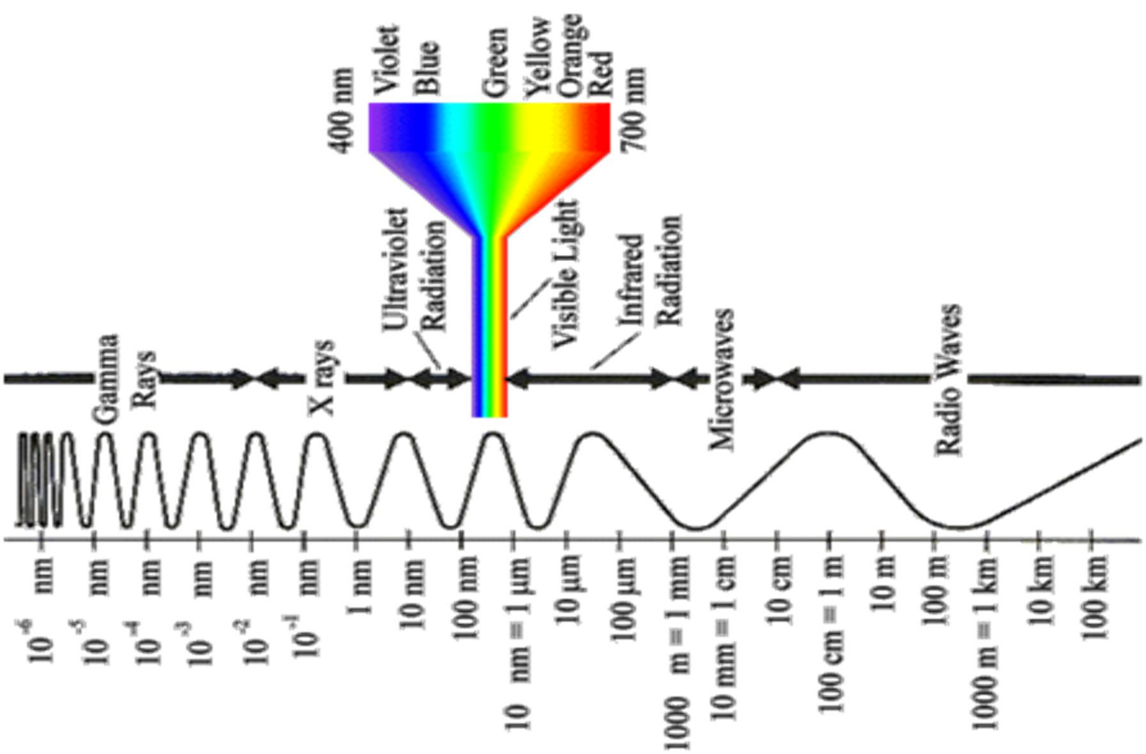
Wave Equation

- $v = f\lambda$
- v = velocity in m/s
  - Velocity of light in vacuum is 300×10^6 m/s
  - Velocity is lower in other media
- f = frequency in hertz (Hz)
  - symbol υ (nu) is sometimes used instead of f
- λ = wavelength in m

Electromagnetic Spectrum

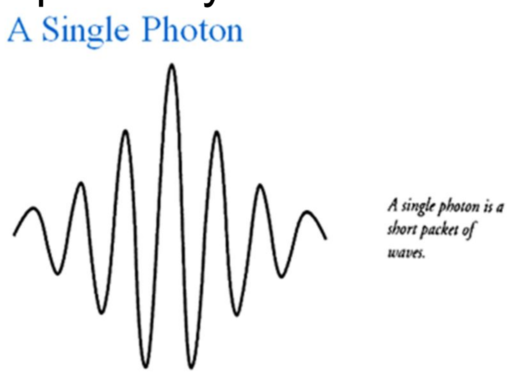
The wave is composed of a combination of mutually perpendicular electric and magnetic fields the direction of propagation of the wave is at right angles to both field directions, this is known as an ELECTROMAGNETIC WAVE


THE ELECTROMAGNETIC SPECTRUM
Wavelength (in meters)
10^3 10^2 10^1 1 10^-1 10^-2 10^-3 10^-4 10^-5 10^-6 10^-7 10^-8 10^-9 10^-10 10^-11 10^-12
longer
shorter
Size of a wavelength
Soccer Field
House
Baseball
This Period
Cell
Bacteria
Virus
Protein
Water Molecule
Common name of wave
RADIO WAVES
INFRARED
VISIBLE
ULTRAVIOLET
"HARD" X RAYS
MICROWAVES
"SOFT" X RAYS
GAMMA RAYS
Sources
AM Radio
rf Cavity
FM Radio
Microwave Oven
Radar
People
Light Bulb
The ALS
X-Ray Machines
Radioactive Elements
Frequency (waves per second)
10^6 10^7 10^8 10^9 10^10 10^11 10^12 10^13 10^14 10^15 10^16 10^17 10^18 10^19 10^20
Energy of one photon (electron volts)
lower
higher
10^-9 10^-8 10^-7 10^-6 10^-5 10^-4 10^-3 10^-2 10^-1 1 10^1 10^2 10^3 10^4 10^5 10^6


400 nm
Violet
Blue
Green
Yellow
Orange
Red
700 nm
Gamma Rays
X rays
Ultraviolet Radiation
Visible Light
Infrared Radiation
Microwaves
Radio Waves
10^-6 nm
10^-5 nm
10^-4 nm
10^-3 nm
10^-2 nm
10^-1 nm
1 nm
10 nm
100 nm
1000 nm = 1 µm
10 µm
100 µm
1000 µm = 1 mm
10 mm = 1 cm
10 cm
100 cm = 1 m
10 m
100 m
1000 m = 1 km
10 km
100 km

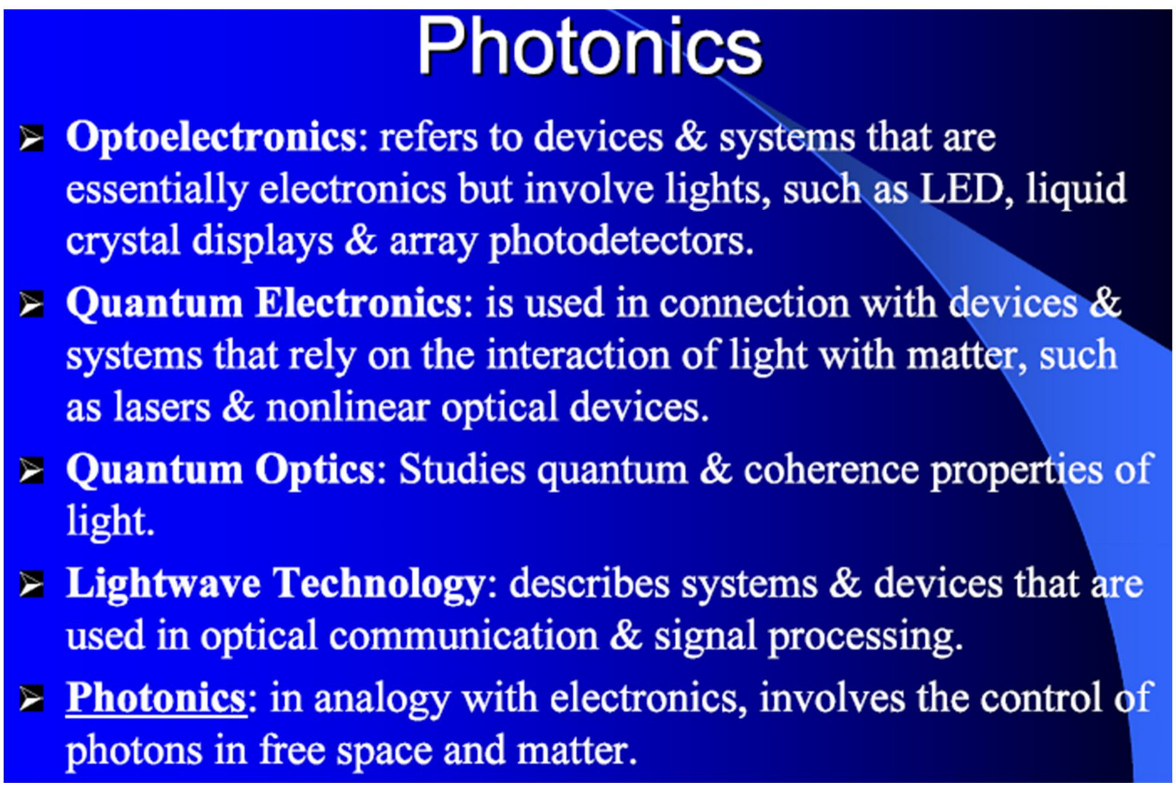
3- Photons

In many contexts light behaves as though it consists of tiny particles called "photons". The explanation (due to Einstein) is that light consists of tiny particles (photons). A single photon dislodges a single electron and gives up all of its energy to the electron. In this case, a beam of light is composed of a stream of small lumps or QUANTA of energy, known as PHOTONS. Each photon carries with it a precisely defined amount of energy defined as:



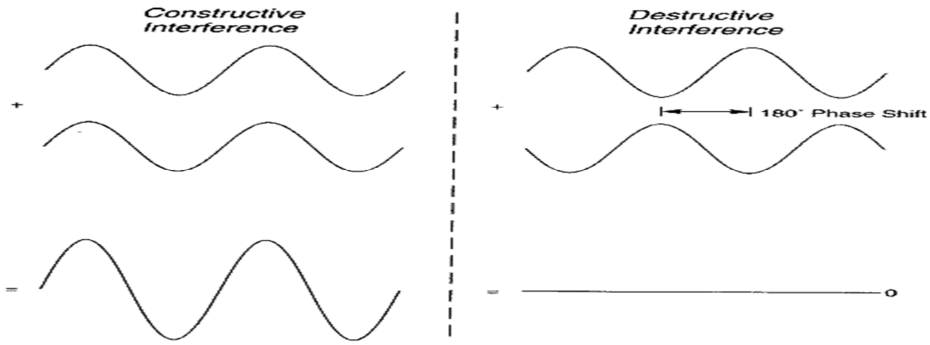
Photon Energy

- $E = hf$
- E = energy of 1 photon in Joules (J)
- h = Planck's constant: 6.626×10^{-34} J-s
- f = frequency in Hz



Interference

- Waves can add constructively or destructively depending on their relative phase
- This happens only with coherent light of one frequency and phase
- White light does not show interference because it has many wavelengths and all possible phase angles.



Constructive and destructive interference.

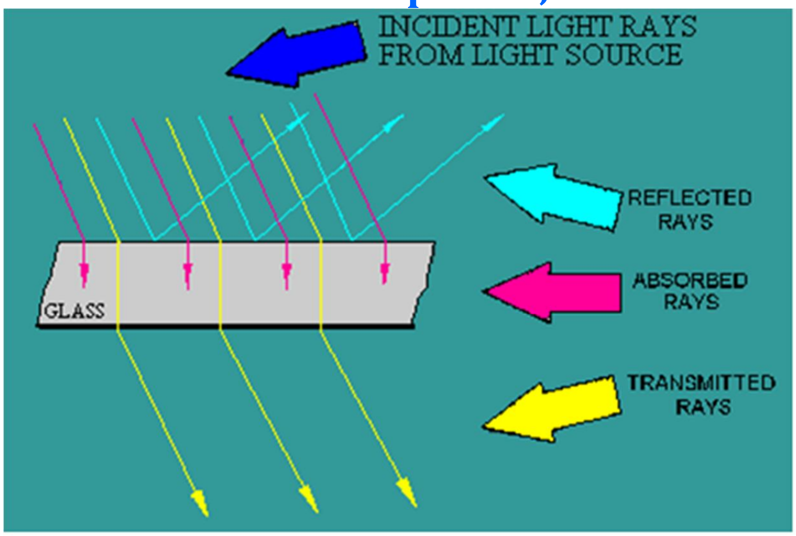
BASIC OPTICAL-MATERIAL PROPERTIES

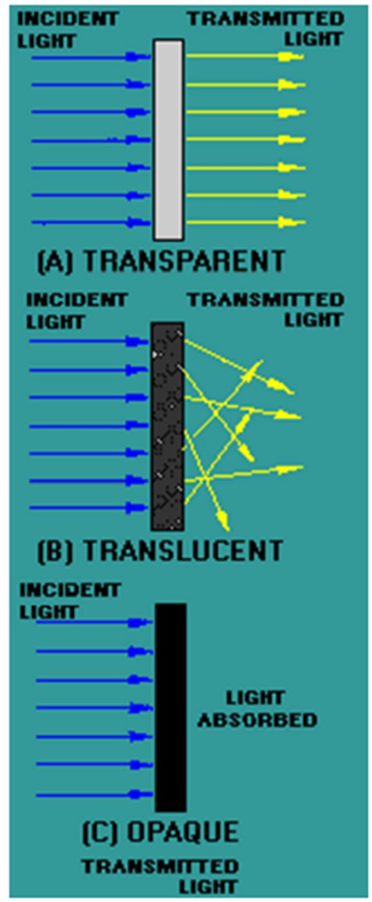
- The basic optical property of a material, relevant to optical fibers, is the index of refraction. The index of refraction (n) measures the speed of light in an optical medium. The index of refraction of a material is the ratio of the speed of light in a vacuum to the speed of light in the material itself. The speed of light (c) in free space (vacuum) is 3 X 10^8 meters per second (m/s). The speed of light is the frequency (f) of light multiplied by the wavelength of light. When light enters the fiber material (an optically dense medium), the light travels slower at a speed (v). Light will always travel slower in the fiber material than in air. The index of refraction is given by: $n = \frac{c}{v}$

PROPERTIES OF LIGHT

- **LIGHT RAYS, when they encounter any substance, are either transmitted, refracted, reflected, or absorbed.**

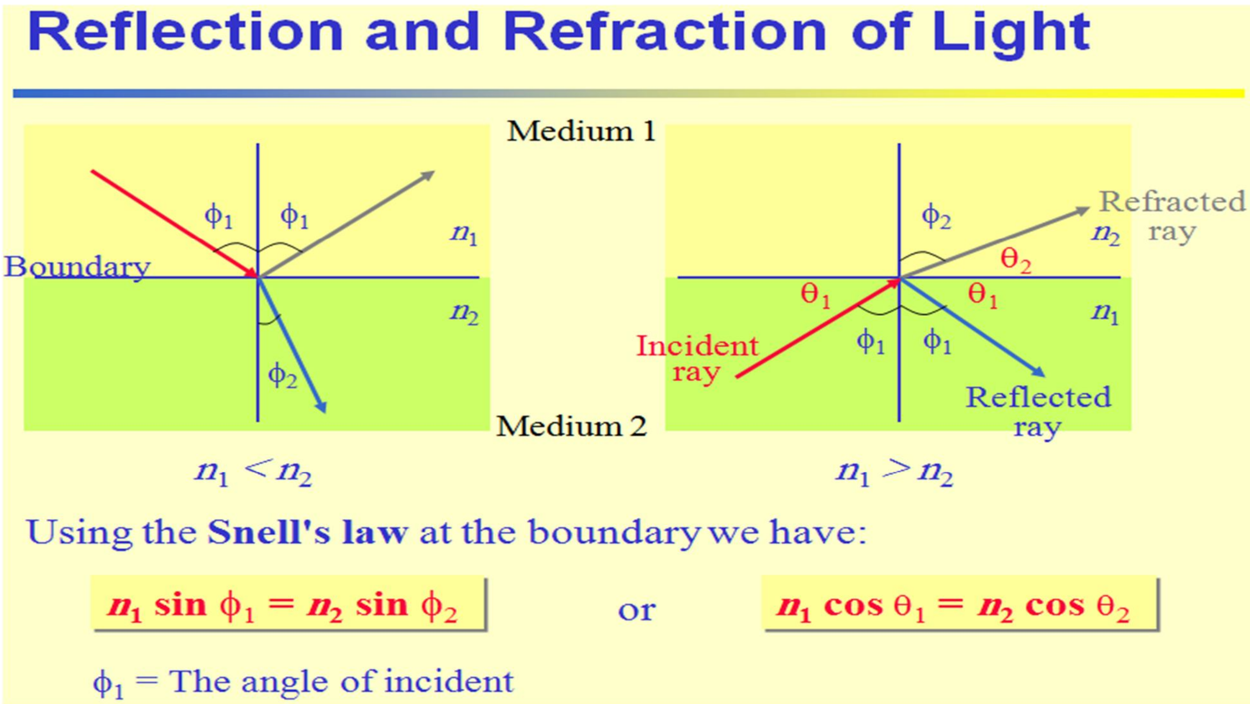
Substances: A. Transparent; B. Translucent; and C. Opaque





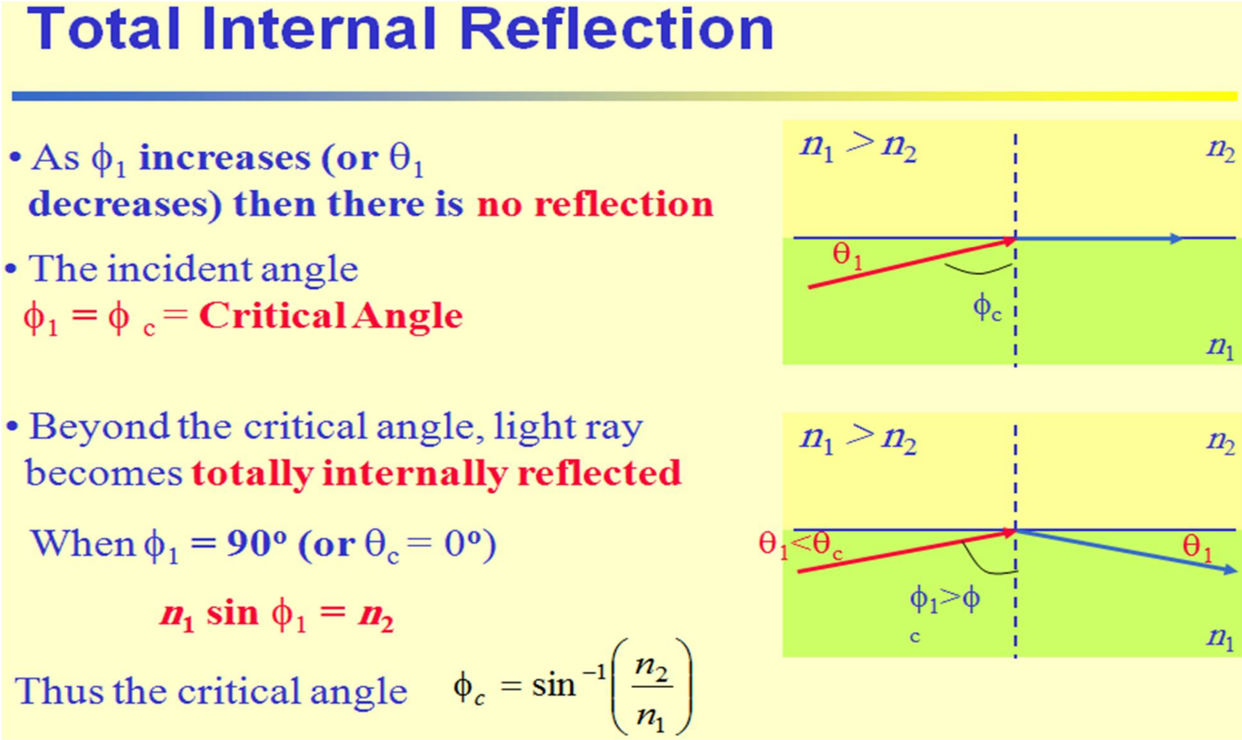
The ratio of the speed of light in a vacuum to that in matter is the index of refraction n of the material $n = \frac{c}{v}$

For air n= 1, 1.33 for water, 1.5 for glass, 2.42 for diamond



Snell's Law

Snell's Law describes how a light ray behaves when it passes from a medium with index of refraction n_1, to a medium with a different index of refraction, n_2. In general, the light will enter the interface between the two medii at an angle. This angle is called the angle of incidence. It is the angle measured between the normal to the surface (interface) and the incoming light beam (see figure). In the case that n_1 is smaller than n_2, the light is bent towards the normal. If n_1 is greater than n_2, the light is bent away from the normal (see figure below). Snell's Law is expressed as $n_1 \sin\theta_1 = n_2 \sin\theta_2$.



1. What is the speed of light in meters per second and in miles per second in the following materials:
   a. air, n = 1.00
   b. water, n = 1.33
   c. CR39, n = 1.498
   d. Crown glass, n = 1.523
   e. Polycarbonate, n = 1.586
   f. Barium glass, n = 1.60 [it actually varies based on the barium content of the glass.]
   g. Flint glass, n = 1.70 [ditto based on lead content.]
   h. cornea of the eye, n = 1.376 [or there-about]
   i. lens of the eye, n = 1.413 [ditto]
   j. aqueous, vitreous, and tear film of the eye, n = 1.34 [averages]
2. What is the index of a material if the speed of yellow light in it is [these are made up, and may not be existing materials]
   a. 100,000 miles/second
   b. 2.5×10^8 meters/second
   c. 93,000 miles/second
   d. 1.589×10^8 meters/second
   e. 152,000 miles/second
   f. 2.11×10^8 meters/second
3. What is meant by the critical angle of a material?

4. What happens if a ray of light attempts to leave a diamond (n = 2.45) at an angle of 30 degrees to the normal, which is greater than the critical angle of diamond in air [24 degrees]?
5. A ray is incident on a material with an index of 1.50 at an angle of 56 degrees to the normal. If the ray is traveling from air what is the angle of refraction? (Round to the nearest degree.) What is the angle of deviation? What is the speed of light in miles/second in this material?
6. A ray of light exits from a material with index of 1.80, traveling into air. If the angle of refraction is 20 degrees, what was the original angle of incidence? (Round to the nearest degree.) What is the angle of deviation? What is the speed of light in miles/second in this material?
7. If a ray of light travels from air into a transparent material at a 26 degree angle to the normal to the surface, and it is refracted through an angle of 16 degrees, what is the index of refraction of the unknown material? (Round to two decimal places.) What is the angle of deviation? (Round to the nearest degree.) [The first question is actually a practical question. We can take an unknown material, make a block with flat polished sides, shine a laser beam through it where we can measure both the angle at which the laser enters the block and where it is while it is traveling through the block, and compute the index; and from that we can actually compute how fast the light is traveling in the material!]